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The Physical Properties of LBGs at z>5: Outflows and the "pre-enrichment problem"

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Abstract. We discuss the properties of Lyman Break galaxies (LBGs) at z>5 as determined from disparate fields covering approximately 500 arcmin^2. While the broad characteristics of the LBG population has been discussed extensively in the literature, such as luminosity functions and clustering amplitude, we focus on the detailed physical properties of the sources in this large survey ($\gtrsim$100 with spectroscopic redshifts). Specifically, we discuss ensemble mass estimates, stellar mass surface densities, core phase space densities, star-formation intensities, characteristics of their stellar populations, etc as obtained from multi-wavelength data (rest-frame UV through optical) for a subsample of these galaxies. In particular, we focus on evidence that these galaxies drive vigorous outflows and speculate that this population may solve the so-called "pre-enrichment problem". The general picture that emerges from these studies is that these galaxies, observed about 1 Gyr after the Big Bang, have properties consistent with being the progenitors of the densest stellar systems in the local Universe – the centers of old bulges and early type galaxies.

1. High Redshift Galaxies and Cosmology

Galaxies at the highest redshifts, z>5, are vital objects in observational cosmology. They formed during an era of one of the most dramatic phase changes in the history of the Universe – the epoch of reionization. Remarkably, these earliest galaxies were able to dictate the phase of the general medium in which all galaxies are imbedded. Because of their enhanced [α/Fe] ratios, which are the product of core collapse supernova enrichment, and old ages, the densest (i.e., globular clusters) and most massive stellar systems (i.e., giant ellipticals) are thought to have formed at such high redshifts in spectacular bursts of star-formation of relatively short duration (<100 Myrs to a 1 Gyr). The short duration of the star-formation but the large accumulated mass must mean that these galaxies had very high star-formation intensities – the rate of star-formation per unit surface area. It is well-known that galaxies with high star-formation intensities drive vigorous outflows of metals and energy. Such outflows from high redshift galaxies could have both cleared material from the galaxian surroundings allowing ionizing photons to escape as well as enriching the intergalactic medium (IGM). Through this mechanism problems of how the IGM was re-ionized and enriched in metals even at the highest redshifts yet observed (this is the so-called "pre-enrichment problem") could be solved. But can we find direct evidence for

this scenario in the physical properties of high redshift galaxies? This is what we will attempt to address here.

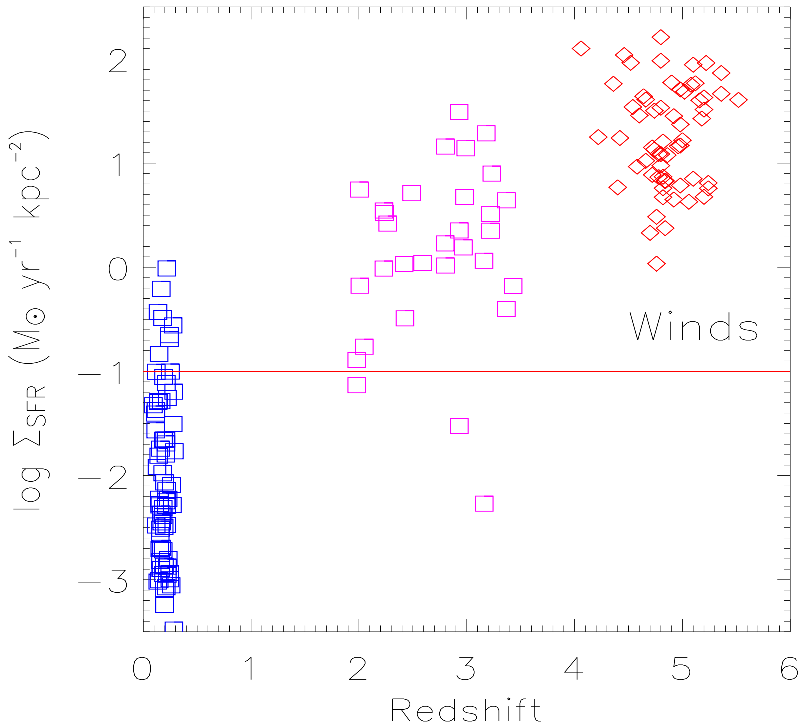

Figure 1. We compare the star-formation rate intensities – the rate of star-formation per unit projected area – of the z≈5 LBGs (diamonds; Verma et al. 2007), z≈3 LBGs (squares; Papovich et al. 2001), and a local sample of UV selected galaxies (squares; Heckman et al. 2005). The horizontal line indicates the threshold above which local starburst exhibit large scale outflows (Heckman 2001; Lehnert & Heckman 1996). All of the galaxies studied here lie above this threshold and thus by analogy, must be driving outflows. We note that the evidence is overwhelming that virtually all z≈3 LBGs are driving outflows (Adelberger et al. 2003).

2. Our Comprehensive Study of z>5 Galaxies

At z∼5, there have been a number of significant spectroscopic surveys investigating the nature of Lyman-break galaxies (LBGs, or "V- or R-band dropouts"), two of which has been lead by some of the authors. There are now over 100 confirmed redshifts in total at z≳5 through the work of our ESO Large Program (the ESO Distant Galaxy Survey – ERGS; Douglas et al. 2007, in preparation) and the study of the "BDFs" (e.g., Lehnert & Bremer 2003; Lehnert et al. 2007, in preparation). The ESO LP is based on the EDIScS fields, which are 10 widely separated intermediate-redshift cluster fields, while the "BDFs" are four adjacent fields observable from Paranal in winter. Our total sample constitutes the largest sample of z>5 LBGs ("R-band drop outs") with spectroscopically confirmed redshifts. In all of these fields, we have deep R-, I-, z-band, and IRAC

data (3.6, 4.5, 5.8, and 8.0 μm). Some of the fields also have observations in other optical/infrared bands, including MIPS 24μm data and HST ACS imaging. In addition, we have been studying a similar population of galaxies in the GOODS-S, taking advantage of the deep multi-wavelength data set (Verma et al. 2007).

3. What have we concluded?

From our analysis of some of these extensive data sets (Verma et al. 2007), we conclude:

• The LBGs at z≈5 are young, with typical ages less than 100 Myrs, compact, with typical half-light radii of about 1 kpc, and are rapidly forming stars, 10 to 200 $M_{\odot}$ yr^{-1}. These ages are very young suggesting that they have been intensely forming stars for only a few dynamical times (estimated from stellar mass estimates and sizes). They therefore may likely represent a population of "primordial galaxies".

• These sources are generally so young that they likely did not substantially contribute to reionization. The estimates of their ages from SED suggests that they formed at redshifts of about 6-7. Their contribution to re-ionization would likely be after the Universe was already substantially ionized.

• From SED fitting from the rest-frame UV through optical, the LBGs at z≈5 are typically about a factor of 10 less massive that similarly selected galaxies at z≈3 (few x 10^9 $M_{\odot}$ compared to few x 10^{10} $M_{\odot}$; Shapley et al. 2001). These galaxies represent about 1% of the local mass density (Verma et al. 2007).

• The LBGs at z≈5 have high stellar mass surface densities, $\mu_{\rm stars}\approx$2-6 x 10^8 $M_{\odot}$ kpc^{-2} and have very roughly approximated core phase densities of 10^{-6} pc^3 km^3 s^{-3}. Both of these are similar to that of bulges and spheriods of $M^\star$ galaxies at low redshift.

• The LBGs at z≈5 have high star-formation intensities, well above that needed to drive winds at low redshift, $\Sigma_{\rm SFR}$ >>0.1 $M_{\odot}$ kpc^{-2} yr^{-1} (Figure 1; Heckman 2001; Lehnert & Heckman 1996).

• If the z≈5 drive strong outflows then they may be able to solve the "pre-enrichment problem" – whereby the metallicity of the IGM does not appear to evolve strongly with redshift at least out to almost z=6 (Songaila 2001; Ryan-Weber et al. 2006). Quantitatively (crudely) estimating the likely metal contribution of these galaxies suggests that they are able to solve the pre-enrichment problem (see Figure 2).

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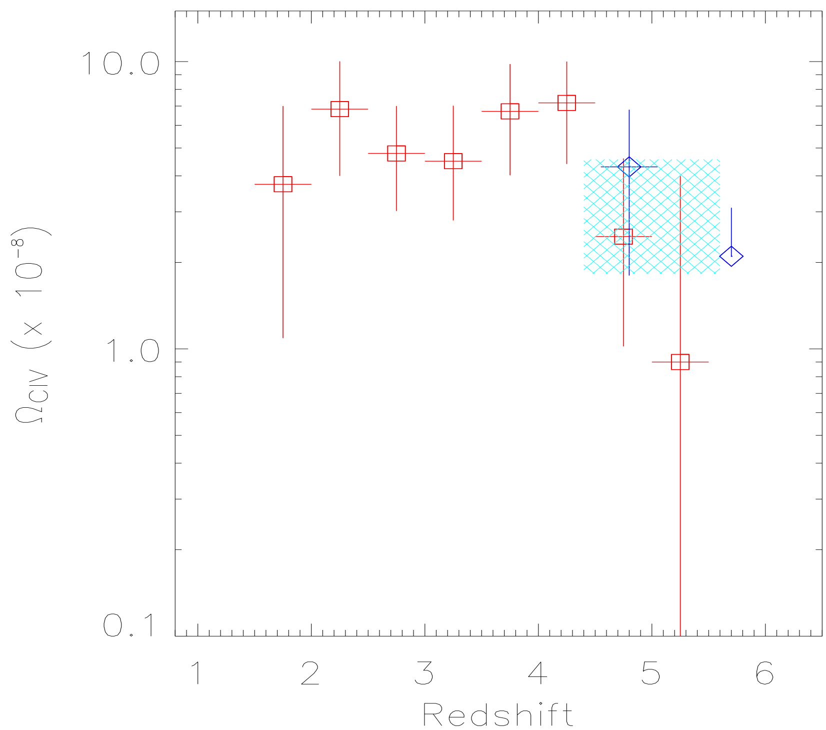

Figure 2. The co-moving density of CIV absorbers does not appear to evolve strongly with redshift (Songaila 2001). This suggests that a large fraction of the metals in the intergalactic medium may have been in place within 1 Gyr after the Big Bang. Comparing the data of the contribution to the closure density due to CIV absorbers, Ω_{CIV} (Songaila 2001; squares, and Pettini et al. 2003; Ryan-Weber et al. 2007; the highest redshift diamond from Ryan-Weber et al. is a lower limit), we find that it is plausible that the z≈5 LBGs could eject sufficient metals to explain the IGM absorption line observations. Our range of estimates was derived assuming that $\dot{M}_{\rm outflow}=\dot{M}_{\rm star-formation}$ (Lehnert & Heckman 1996), the closure density, that the ionization fraction of C^{3+}=0.5, the metallicity of the outflow is 0.2 $Z_{\odot}$, $\Omega_b h^2$=0.023. and the range of star-formation rates derived in Verma et al. (2007).

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